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SILICON AVALANCHE LIGHT SOURCES FOR PHOTOGRAPHIC DATA RECORDING

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ABSTRACT

Although emission of visible light from avalanching silicon p-n junctions has been known and studied for a number of years, practical applications of the phenomena have been limited to photo-multiplier calibration systems by the relatively poor efficiency of the light source.

The mechanism of light generation in the avalanching silicon junction was studied and a structure optimizing light output in a spectrum suitable for photographic recording has been derived. Light from avalanching junctions is emitted as a 3μ wide line source. By a proper choice of source geometry in combination with controlled spacing of the light source from a photographic emulsion, it is possible without optics to record information bits as density dots having a regular and predictable density profile.

Through the use of integrated circuit technology, it is possible to fabricate the sources into rectangular matrix arrays on close spaced centers for recording digital data on photographic film.

An all Solid State Photographic Auxiliary Data Annotation System has been designed incorporating the Silicon Light Pulser Matrix. The data handling and annotation system equipment is designed to service a complete Reconnaissance System consisting of photographic, radar, and infrared systems.

The system complies with the recently adopted Military Standard for Tactical Reconnaissance Data Marking. The advantages of the new techniques as contrasted to conventional miniature cathode ray tube system are indicated.

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SILICON AVALANCHE LIGHT SOURCES FOR PHOTOGRAPHIC DATA RECORDING

Emission of visible light from avalanching silicon p-n junctions has been studied in some detail by many workers over the past decade. Chynoweth and McKay of Bell Telephone Laboratories have published descriptions (1) of the phenomenon and results of investigations into spectral distributions and efficiencies of light generation. Because of the relative inefficiency of this means of generating light, no practical applications of the phenomenon were made until 1960 when Fairchild Semiconductor began to market a silicon light pulser device for use in calibrating nuclear event detection systems. This application resulted from the extremely rapid turn-on and turn-off characteristic of the light pulser (less than 3 nsec) that made it possible to simulate scintillation pulses from nuclear event counters.

At the beginning of 1963 our work in exploring various possibilities of computer memories involving the recording of digital data on photographic film prompted additional investigation of the silicon avalanche light source. This work resulted in a device structure that improved the emission efficiency in the blue end of the spectrum by an order of magnitude, and made it possible to design an integrated circuit matrix array of light pulsers for recording digital data on photographic film.

The fundamental mechanism considered responsible for the emission of light from the avalanching junction is radiative transitions of "hot" charge carriers crossing the junction under the influence of the intense electric field on the order of 10^6 volts per centimeter existing in the depletion layer of the avalanching junction. These hot carriers have a broad distribution of energy and, therefore, the spectral distribution of the photons emitted on recombination is fairly broad. If transitions occur deep in the bulk of the silicon, most of the shortwave length photons are absorbed by the silicon and the emitted light peaks sharply in the red and infrared portions of the spectrum. However, by designing a structure which forces the avalanche breakdown to occur close to the silicon surface, an appreciable amount of light can be generated in the blue-green region of the spectrum and the emitted light will appear as a warm white to the eye. In the optimized structure developed for the photographic recording application, the spectral distribution of the emitted light over the visible region (as shown in Fig. 1) approximates the radiation from a black body having a color temperature of 2500°. This spectral distribution is achieved by fabricating a diffused structure that forces the avalanche breakdown to occur within a few tenths of a micron from the surface of the silicon (as illustrated in Fig. 2).

Microscopically, the light source appears as a line source having a brightness at maximum usable current density levels estimated to be in the range of 5000 ft.-lamberts. However, this high brightness value must not be confused with a high total light output because the emitting area is extremely small. The light is emitted from a line source and, in the matrix array, this line source is actually 6 mils in length and 0.3 microns wide.

Therefore, at a junction avalanche current of 100 ma, the total emitted light is 1.9×10^{10} visible photons per second and emission efficiency over the visible range is 3×10^{-8} photons per charge carrier crossing the junction. However, in spite of the low efficiency and low total output, sufficient light is emitted to expose moderate speed film to saturation density in times on the order of 1 millisecond.

Light emitted from the junction line source approximates a cosine distribution of intensity because a uniform oxide protects the planar structure where the junction intersects the surface of the silicon. Light emitted from regions below the surface will be transmitted through the surface only over the angle permitted by the index of refraction of silicon relative to air. The extreme rays at the critical angle will be parallel to the surface of the silicon, and intensity will increase following a cosine law as the angle of emission approaches the normal to the silicon surface.

In the film recording of digital data, it is desirable that the data bit be recorded as a round dot having a density profile 8 mils in diameter at the 50% transmission point and a flat top of approximately 5 mils diameter. Because the light is emitted from essentially a line source, a means of producing a round, uniformly dense dot of finite area from this source must be devised. The problem is solved by spacing a photographic emulsion at the proper distance from the source and shaping the source to approximate a circle so that the lambertian distribution of light from each point in the source combines at the emulsion plane of the recording material to provide the desired density profile. An actual enlarged photograph of an active single data bit light source in the array is shown in Figure 3. Figure 4 illustrates a series of constant illuminance contours for two spatially separated point sources, indicating how the desired density profile is achieved by spacing the recording emulsion at a given distance from the light source.

The data recording format consists of a block of dots arranged in a rectangular matrix with dots spaced on 18 mil centers. The block consists of 32 rows and 6 columns of dots. An enlarged photograph of an actual recording of a typical data pattern is shown in Figure 5. Such a format precludes the use of individual devices without optical systems, and it was therefore necessary to integrate an array of 192 devices into a monolithic silicon chip. Technology has now been extended to produce a recording matrix in a single integrated circuit chip containing over 500 active devices.

A recording light source chip consists of diffusion isolated p-n junctions (as shown in Fig. 6), fabricated in silicon by the Planar technology and interconnected by standard metal-over-oxide techniques so that a single light pulser is energized by making electrical connections to the appropriate row and column of the matrix array. Crossover of the interconnecting busses is accomplished by using the oxide-protected isolation diffusions as the interconnections between the metalized row interconnect bars shown in the figure.

An actual recording head utilizing the silicon light pulser array as packaged for installation in a recording system is illustrated in Figure 7.

Applications requiring the photographic recording of data in dense dot formats have been studied, and indicated that the solid state record technique has significant advantages to offer.

Military applications require that the record system be rugged to sustain severe environments, small in size, light in weight, and reliable with a large mean time between failure.

The need for dense data recording systems is usually complemented with the need for a corresponding data reading system. The latter's feasibility and complexity is dependent on the geometric stability of the recorded data pattern, and the degree of uniformity of the recorded dot characteristics both within a single data format and between all generated data formats.

A comparison of the Solid State Record System will be made on the above parameters with a currently used technique wherein a miniaturized CRT is used.

The Solid State Record Head is extremely rugged since the construction yields a compact cubical entity. There is no requirement to isolate this device from shock and vibration since the environments do not affect its operation any more than they affect the operation of Planar integrated logic devices.

The CRT is a relatively fragile device. It contains a glass enclosed vacuum cavity and its gun elements and deflection system are very susceptible to vibration and shock. Without suitable provisions for isolation from these

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environments the life of the tube should be greatly reduced.

The Solid State Record Head has the physical dimensions of 0.875 inch square cross section with 0.875 inch height. The weight of this head including cable and connectors is 6 ounces.

The CRT Record Head is approximately 4.5 inch long with 1.25 inch diameter and weighs approximately 1 pound. This value does not include weight of associated optics.

The Solid State Record Head, because of its small size, mounts directly through the cutout in the camera format plate and eliminates any need for an optical system. In several such installations, data patterns suitable for automatic reading were obtained.

The CRT, because of the sizeable variation in the face thickness of the tube, cannot be used as a direct recording system but requires a high resolution optical focusing system. In cases where there is insufficient room to mount the CRT and the lens directly behind the cutout in the camera format plate a high resolution optical transmission system would be required.

The Solid State Record Head offers extremely high reliability. All fabrication techniques used in the manufacture of the array have been previously used on the Fairchild integrated circuit production line.

Thirteen individual light pulsers have been subjected to a life test consisting of 1/2 billion cycles each. The devices were operated at 500 cps for a 4 week period at a 0.5% duty cycle. The light output measurements indicated no variation of light output. No other light source known begins to approach this sort of life.

The CRT has the following aging problem. Light emission from the phosphor on the face of the CRT decreases as the accumulated exposure increases. Those data dots that are energized most frequently, such as index dots, will age fastest. Those data spots that are rarely energized will show little aging. Typical specifications allow peak dot variation of 30% of the maximum over the data format. It is quite possible for this to occur within the half life of the tube, which for small diameter tubes is 1000 hours.

The Solid State Record Head represents the ultimate in stability of the data format presented. Each data binary bit is represented by a unique 2 mil square area. The dot to dot peak density variation is limited to less than 10% by the uniformity of characteristics of all devices manufactured on the same chip. The dot to dot dimensional error is unvarying and is determined by the manufacturing process. Present techniques limit this error to 0.5 mil in the 18 mil dot pitch. All data formats from any Record Head will be exactly the same. Interdot space being inactive semiconductor never emits light.

The CRT Record Head represents the worst possible stability in the data format. The whole face of the tube is covered by the light emitting phosphor. There is no direct physical correspondence between data bits and points on the tube face. The correspondence is established by means of gun emission of electrons and suitable deflections as the electrons traverse a path along the axis of the tube. In this technique a host of technical problems become extremely important - rigidity of gun and deflection structures under adverse environments; tight focus of an electron beam; deflection susceptibility to stray electric and magnetic fields; spreading of light emission within the phosphor; light emission between the lighted dot areas due to stray electrons activating this phosphor.

CONCLUSION

The solid state technique for digital data recording provides greater reliability, longer life, and ease of integration into recording equipment.

In addition to the advantages listed, this technique provides greater immunity from radio frequency interference and vibration effects encountered in military and other environments. It is in these areas that major advantages are possessed by this technique which may escape attention but which cause great difficulty in currently used approaches. The increased immunity to these effects provides indirect weight and cost savings in a photographic data recording system based upon the solid state device which may not appear in a table of comparison.

Another indirect advantage is provided by the closer adherence of the recorded data to a specified geometrical arrangement than is possible with other recording methods. This improvement in recorded output quality improves the ability of machine reading equipment to provide error free readout.

ACKNOWLEDGEMENTS

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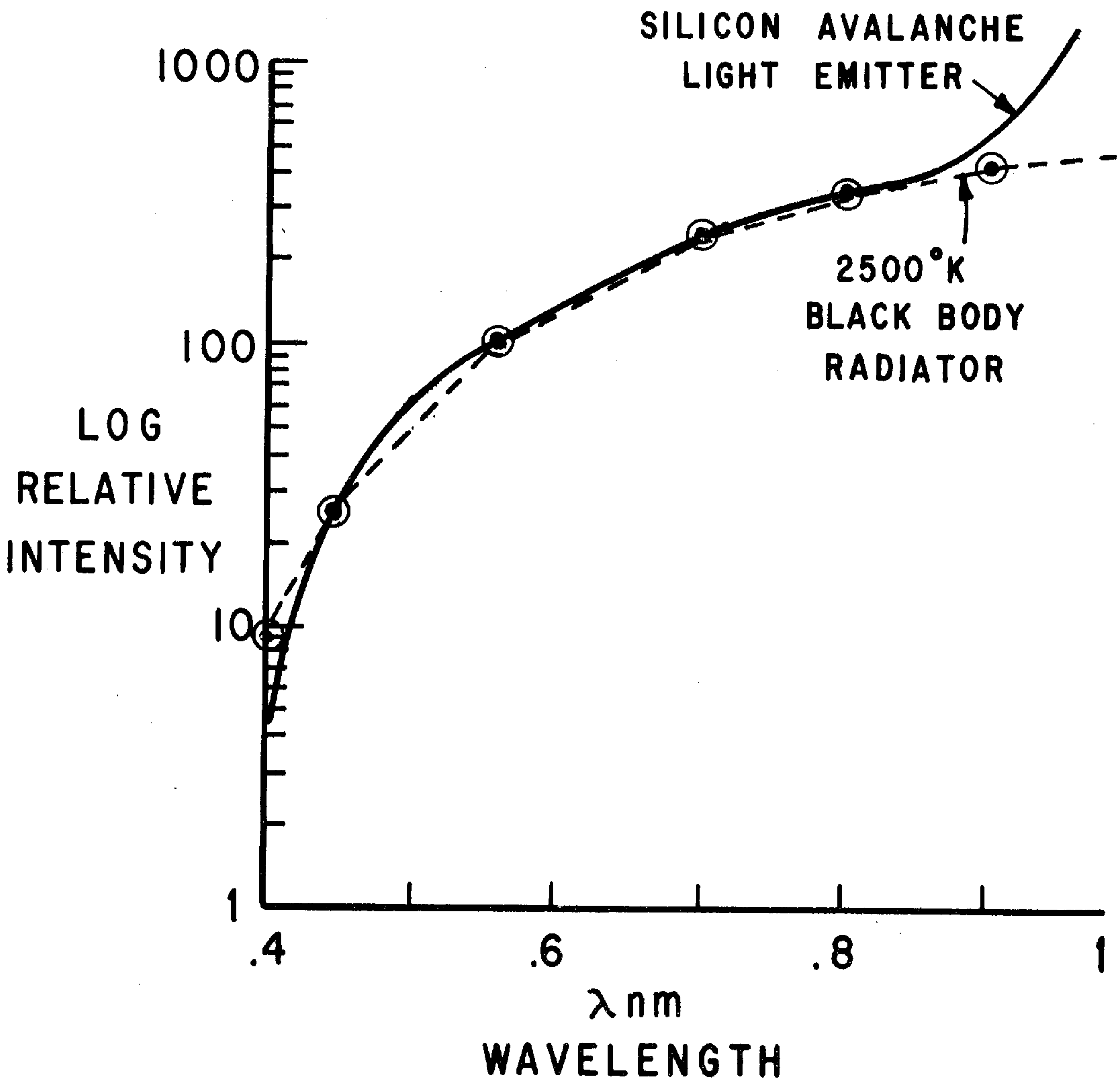

FIGURE 1. TYPICAL SPECTRAL DISTRIBUTION OF AVALANCHING JUNCTION LIGHT OUTPUT

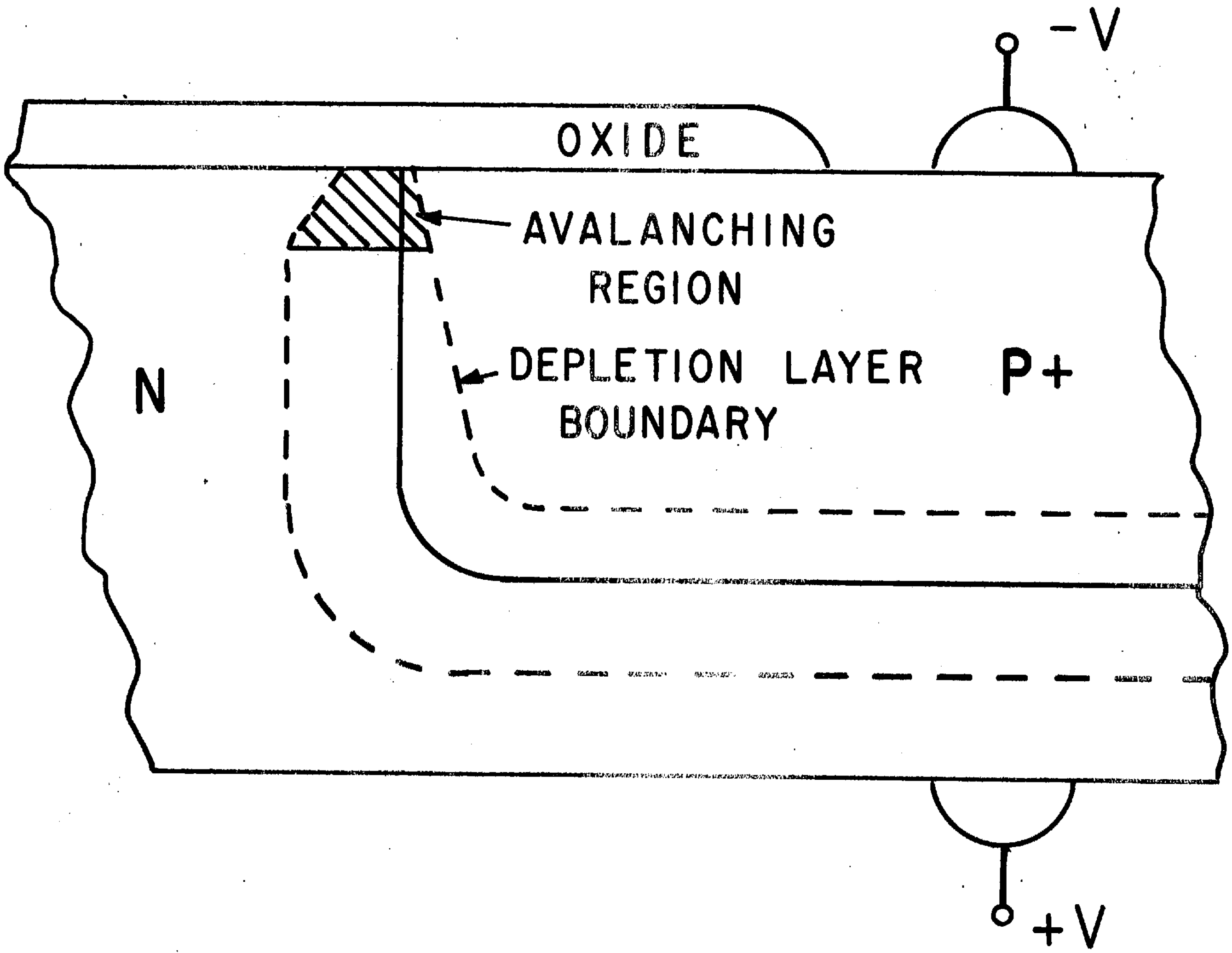

FIGURE 2. JUNCTION PROFILE

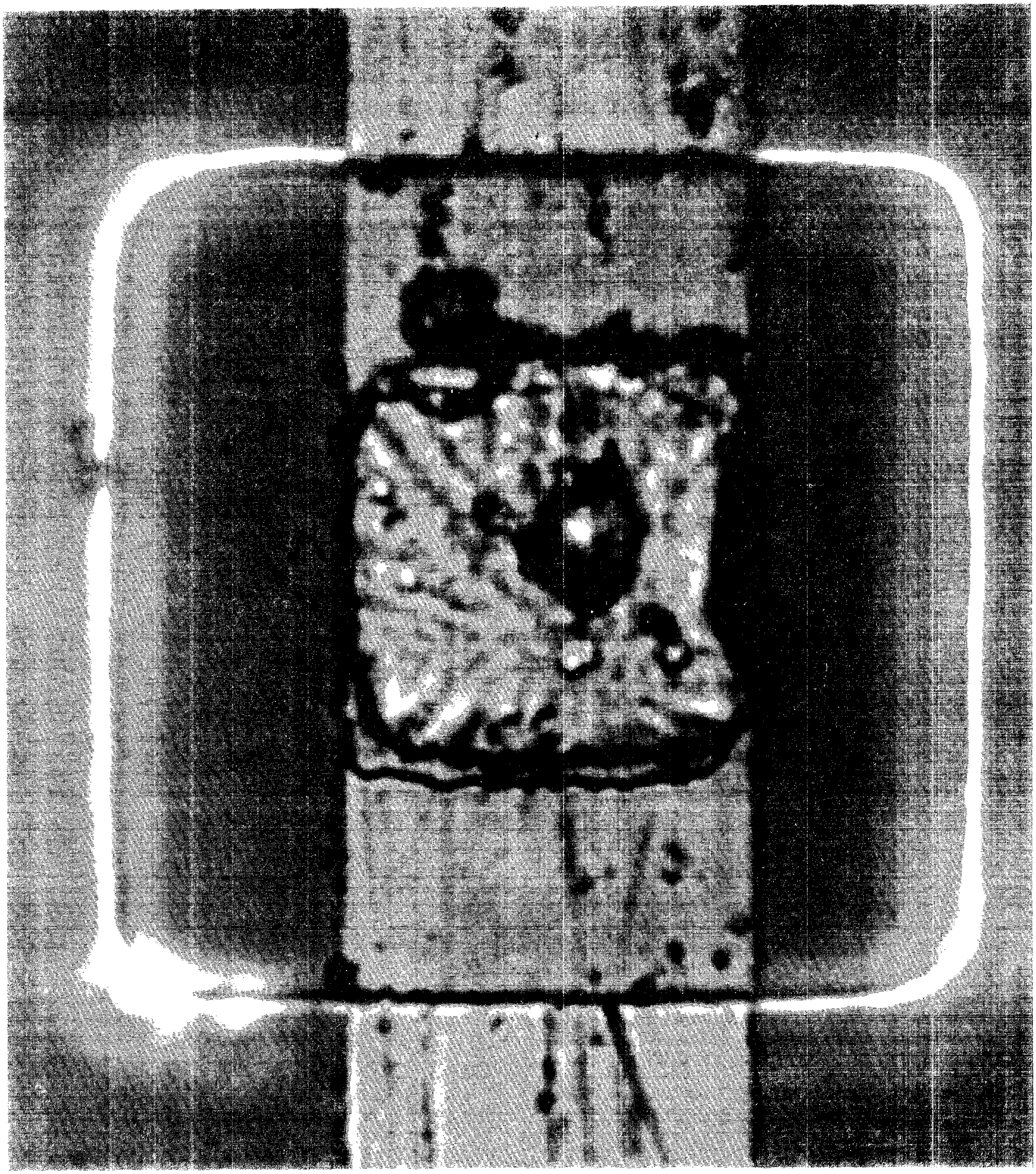

FIGURE 3. SILICON JUNCTION EMITTING AVALANCHE LIGHT

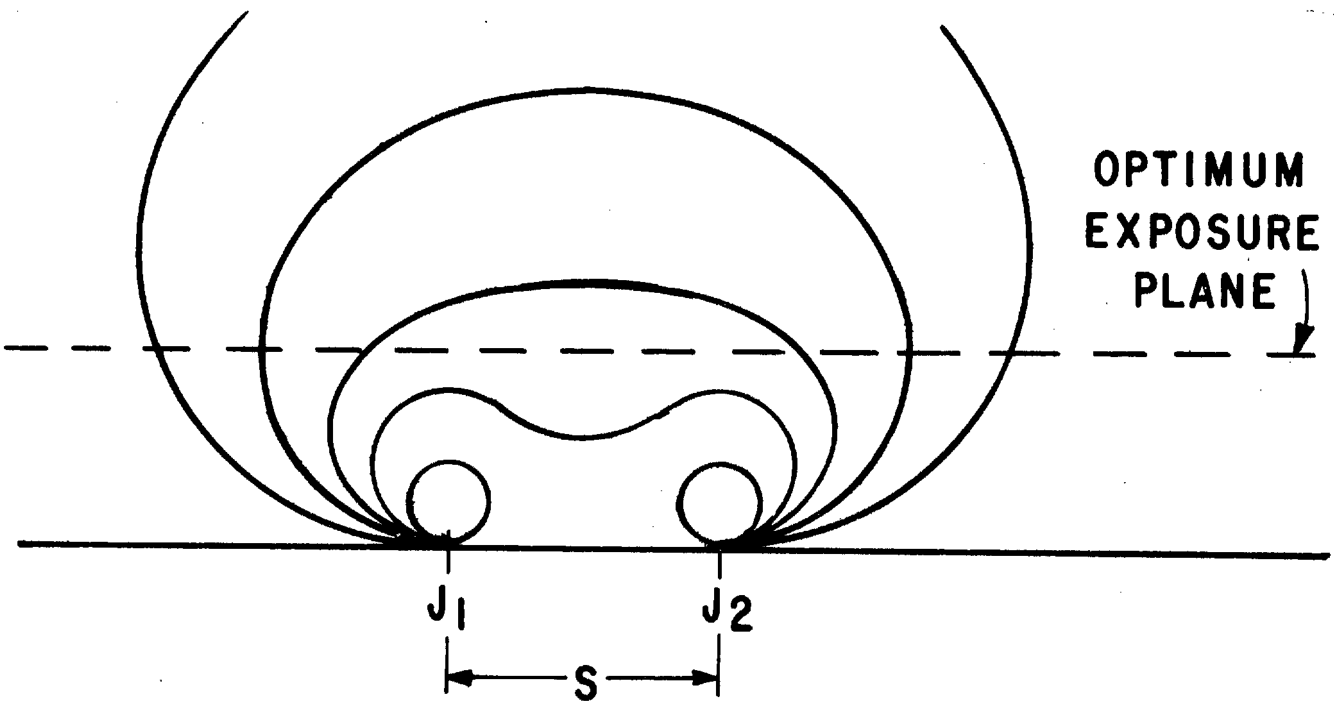

FIGURE 4. CONTOURS OF CONSTANT ILLUMINATION FOR PARALLEL RECEIVER

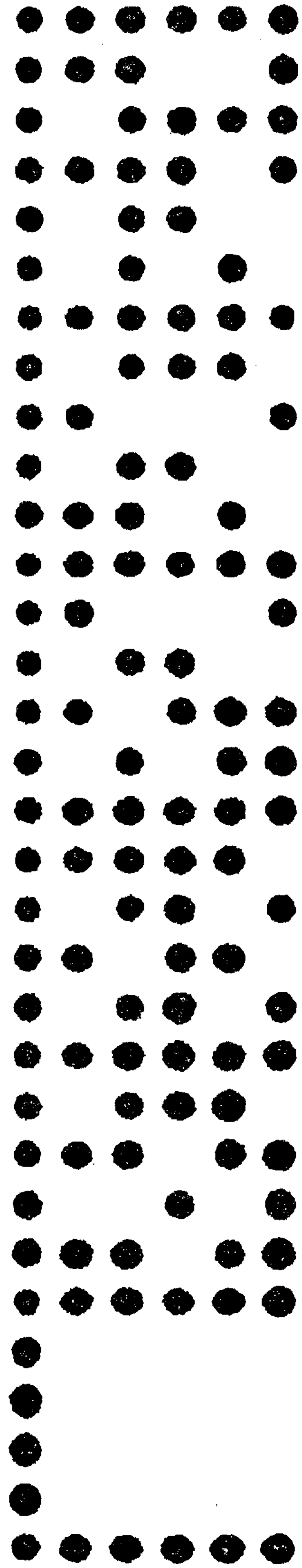

FIGURE 5. DATA PATTERN RECORDED WITH SILICON LIGHT SOURCE

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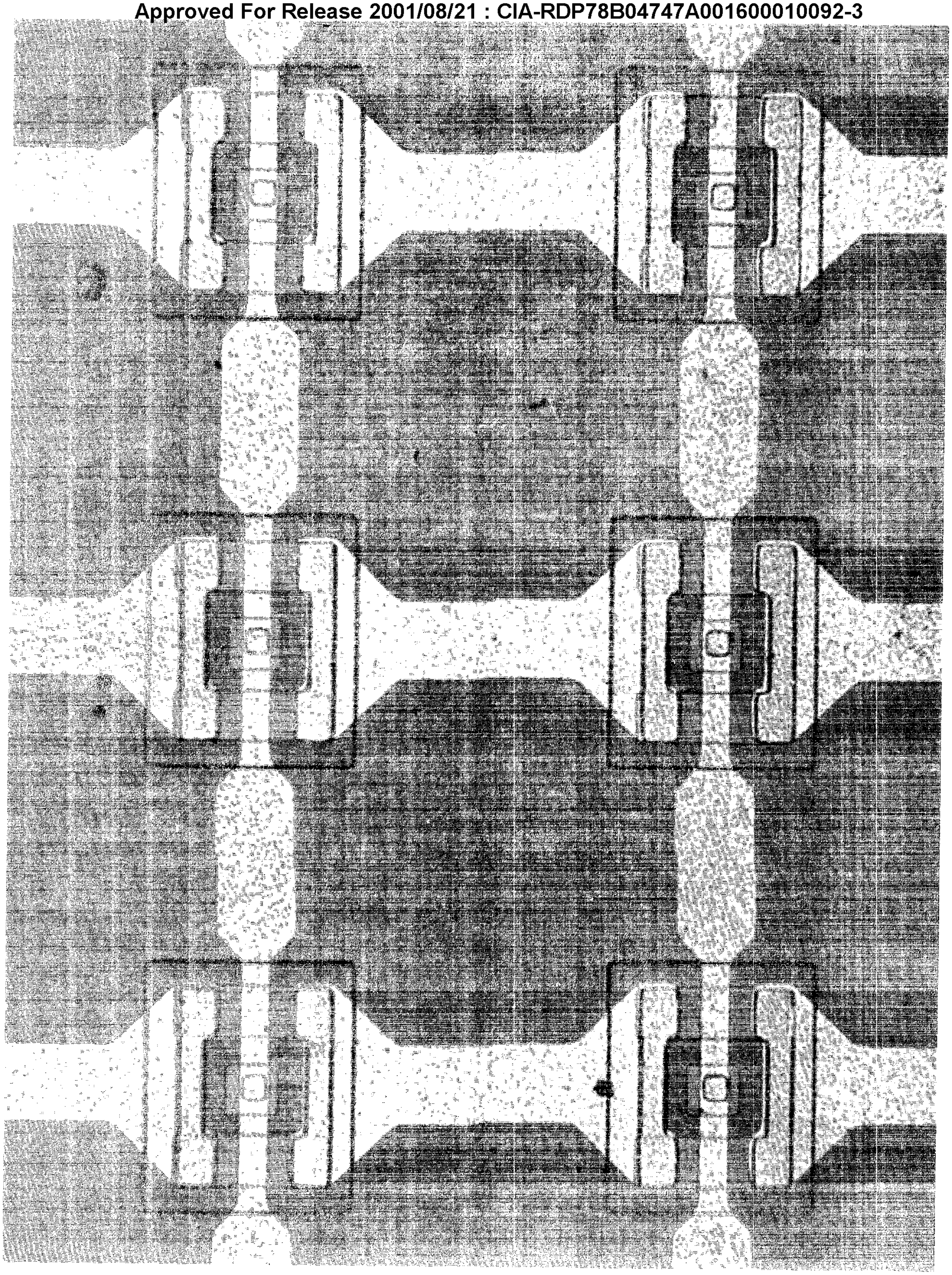

FIGURE 8. SILICON LIGHT SOURCE ARRAY STRUCTURE

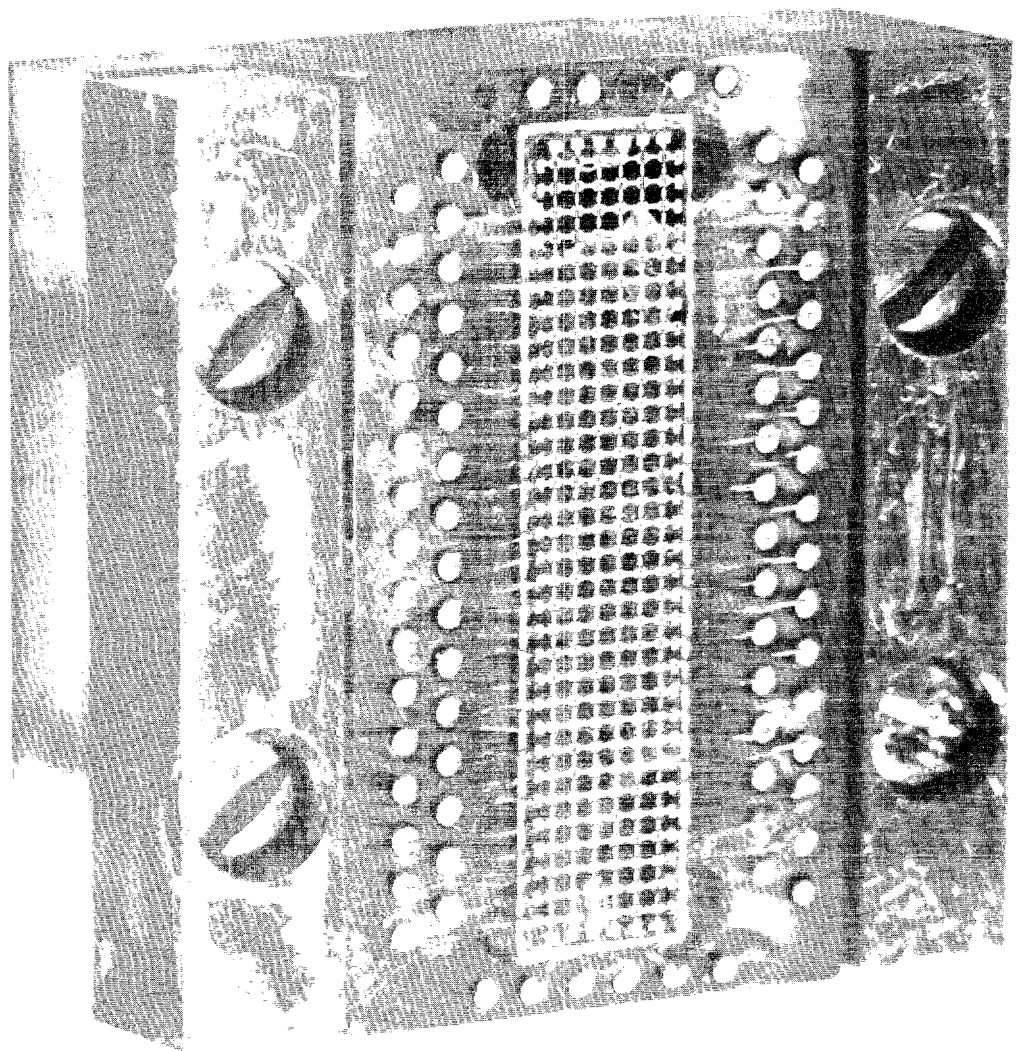

FIGURE 7. DIGITAL DATA RECORDING HEAD

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